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***Abstract*—The J-PARC Neutrino Experiment, the construction of which starts in JFY 2004, will use a superconducting magnet system for its primary proton beam line. The system, which bends the 50 GeV 0.75 MW proton beam by about 80 degrees, consists of 28 superconducting combined function magnets. The magnets utilize single layer left/right asymmetric coils that generate a dipole field of 2.6 T and a quadrupole field of 18.6 T/m with the operation current of about 7.35 kA. The system also contains a few conduction cooled superconducting corrector magnets that serve as vertical and horizontal steering magnets. All the magnets are designed to provide a physical beam aperture of 130 mm in order to achieve a large beam acceptance. Extensive care is also required to achieve safe operation with the high power proton beam. The paper summarizes the system design as well as some safety analysis results.**

***Index Terms*—Accelerator safety, Neutrinos, Particle beam transport, Superconducting accelerator magnets,**

I. Introduction

THE Tokai-to-Kamioka Neutrino experiment (T2K) [1][2] is a next generation neutrino oscillation experiment. The experiment will use the J-PARC 50 GeV, 0.75 MW proton beam [3] to create a high intensity neutrino beam targeted to the Super-Kamiokande neutrino detector, which is located 295 km west of J-PARC. The facility consists of a proton beam line that bends the proton beam about 87 degree with a radius of about 105 m, a target that create pions from the high intensity proton beam, and a decay volume in which pions decay into muon neutrinos (and muons). The construction of the facility is approved to start in JFY 2004 and planned to be complete in JFY 2008. Due to the limited bending radius, the proton beam line requires a superconducting magnet system [4] to bend the 50 GeV proton beam. The superconducting magnet system consists of 28 combined function magnets, which create dipole and quadrupole fields simultaneously with single layer left-right asymmetric coils. The design is chosen to minimize the construction costs of the superconducing magnet system. The system is also equipped with conduction cooled dipole corrector magnets, which serve as vertical and horizontal steering magnets. The paper summarizes the magnet and the cryogenics design. The development status of the magnets and the safety issues of the system are also reported.

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II. Magnets

A. Combined Function Magnets

The cross section of the magnet is shown in Fig. 1, and its main parameters are summarized in Table I.

The coils are wound from the conductor used for the CERN-LHC arc dipole magnet outer layer coil. Polyimide tape coated with 10 µm thick B-stage epoxy glue, the same system as that of LHC insertion quadrupole magnets developed by KEK (MQXA) [5], is used for the conductor insulation. The coil inner diameter is 173.4 mm and the outer diameter is 204 mm. The pole of the coil is rotated towards the high field side by about 20 degrees, resulting in a left/right asymmetric dipole-like coil [6]. The 41 turn coil consists of 2 blocks on the high field side and 5 blocks on the low field side. The GFRP (G11) wedge shaped spacers separate those blocks. A pre-stress of 80 MPa is exerted on the coil during the magnet assembly. The coil is cured with an azimuthal oversize of 0.7 mm on the

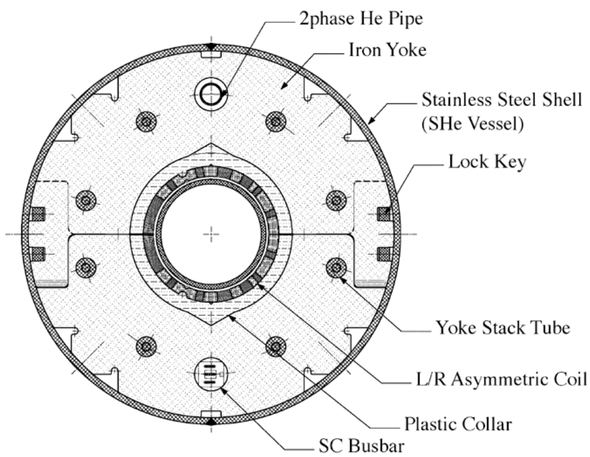

Fig. 1. Cross section of combined function magnet

low field side and 1.0 mm on the high field side to compensate for the difference of the spring constant between the two sides. The pre-stress loss during cool down is expected to be about 20 MPa. The difference of the pre-stress loss between the high field and the low field side during the cool down depends on the amount of the pre-stress loss. A difference of 4 MPa is expected with the 20 MPa loss. During magnet excitation, the asymmetric field produces a difference of pre-stress losses. The pre-stress losses are 22 MPa at the high field side of the pole and 16 MPa at the low field side pole.

TABLE I
MAIN PARAMETERS OF THE SUPERCONDUCTING COMBINED FUNCTION MAGNET

Parameter	Value
Beam Energy	50 GeV
Dipole Field	2.586 T
Quadrupole Field	18.62 T/m
Magnetic Length	3.3 m
Operating Current	7345 A
Operating Temperature	<5 K
Load Line Ratio	75 %
Inductance	14 mH
Stored Energy	386 kJ
Cable	LHC arc dipole outer

The plastic collars are made from glass-fiber filled phenolic plastic, which is equivalent to that used for the RHIC magnets [7]. They are manufactured by compression molding to reduce cost. The collars work as ground insulation, which simplifies the assembly process. The collars also set the azimuthal alignment of the coil with respect to the yoke structure. The size of the collars is controlled within 50 μm accuracy to assure the coil placement. It has been confirmed that the mechanical properties of this material are sufficient, even after irradiation to the level expected in the magnet, to ensure the structural support to the coils.

The yoke consists of two kinds of laminations, fixing laminations (5.8 mm thick) and spacer laminations (6 mm thick). They are sub-stacked in packs about 20 cm long to simplify the yoking process. The laminations are stacked on four stacking tubes, which also provide mechanical support between spacer and fixing laminations. The upper and lower yokes are locked together by steel keys and the lock is made such that the yoke mid-plane will not open. The resulting structure fixes the azimuthal coil size and compresses the coil to the target pre-stress of 80 MPa. The holes at the center of the yoke provide the space to install the tube for the two phase helium return at the top, and the space for the superconducting bus at the bottom.

Construction of the magnet is completed with a 10 mm thick stainless steel shell, which also serves as the helium vessel. The magnet cold mass outer diameter is 570 mm, which is the same as the LHC arc dipole magnets, so that a common baseline design of the cryostat can be used.

The left-right asymmetric coils produce a dipole field of 2.586 T, and a quadrupole field of 18.62 T/m with an operation current of 7350 A. The maximum field at the conductor is 4.57 T in the magnet straight section. In the end region it is 2~3 % higher. The load line ratio to the conductor short sample limit is about 75 % with the maximum operation temperature of 5 K. The magnetic length of the magnet is 3.3 m and the actual physical length of the coil is about 3.6 m. The field quality of the magnet at the reference radius of 5 cm is summarized in the Table II.

TABLE II
FIELD QUALITY OF THE SUPERCONDUCTING COMBINED FUNCTION MAGNET @ 5 CM FOR 50 GEV OPERATION. 2D-SS IS TWO DIMENSIONAL COMPUTATION USING OPERA2D. THE REST OF THE COMPUTATIONS ARE MADE BY OPERA3D.

	2D-SS	3D-SS	3D-LE	3D-RE	3D-Integral
Lmag (m)	3.3	1.94	0.78	0.58	3.3
B1 (T)	2.586	2.591	2.602	2.603	2.601
b2 (unit)	3618	3628	3567	3517	3581
b3 (unit)	1.645	-0.93	-58.1	-101.5	-33.7
b4 (unit)	9.06	5.01	-11.1	-23.5	-2.3
b5 (unit)	2.52	2.07	-8.9	-16.0	-3.5
b6 (unit)	-6.26	-6.36	-7.9	-9.8	-7.2
b7 (unit)	-0.89	-1.16	-3.5	-5.3	-2.4
b8 (unit)	-3.77	-3.95	-2.9	-3.6	-3.7
b9 (unit)	-8.90	-8.86	-7.7	-7.9	-8.4
b10 (unit)	-0.26	-0.25	0.3	0.3	-0.0
b11 (unit)	-3.04	-3.10	-2.7	-2.6	-2.9
b12 (unit)	2.06	2.07	1.7	1.6	1.9

The results were computed using Opera2D and Opera3D [8]. For the 3D computation the coil is separated in three sections, the straight section (SS), the lead end section (LE), and the return end section (RE). The reported values are the field integral created by each section. The computed 3D-SS results are in good agreement with those derived from the 2D computation. They are also in good agreement with the computation results by Roxie [3][9]. The end field quality is not as good as that of SS because of limits to the optimization due to the use of a single layer coil. However, the beam simulation indicates that the field quality is good enough for beam operation. Since the beam line will be operated with a 40 GeV proton beam in the first stage, the magnets have to provide the good field quality for 40 GeV operation. The field quality has been computed and confirmed to be good enough.

B. Corrector Magnets

The corrector magnets are installed in the interconnects between the cryostats. In order to simplify the cryogenic system, conduction cooling is chosen for cooling method. Using the BNL direct winding technology [10], the coils are wound directly on a 1 cm thick copper bobbin, which serves as the major source of the cooling. The bobbin is held at its ends by copper flanges that are thermally connected to the two phase helium cooling channel. The coil is then encased by a 2 cm thick iron yoke, and covered with pure aluminum sheet. The aluminum sheet is also thermally connected to the two phase helium line, and it provides an additional cooling channel as well as radiation shield. The overall length of the magnet is about 800 mm, and two dipole coils, normal and skew, are wound end to end along the magnet length. The maximum required dipole field integral is 0.1 Tm.

C. Powering Scheme

The powering scheme of the combined function magnets is shown in Fig. 2. The all magnets are connected in series and powered by a single power supply. Each of the magnets is protected by a cold diode. The cold diodes are of the same design as that used for LHC arc quadrupole magnets [11][12]. The quench simulation indicated that the magnet current is bypassed to the diode within 1 second and that maximum temperature of the magnet is limited to about 280 K.

The power supply system includes an external dump resistor circuit to shut down the system current. The external resistor is 20 mΩ that gives a decay time constant of 20 seconds with the overall magnet inductance of 400 mH. The circuit is needed to protect the cold diodes from over heating by the bypass current. The time constant is fast enough to protect the cold diodes (see section IV-*C*). The current supply from the power supply at ground level to the underground magnets is made via superconducting bus bars. The bus bar is made with the magnet cable bundled with the three copper cables that have the same dimensions as the superconducting cable. The same bus bars are used to connect the magnets in series. The bus bar is designed such that it can carry the 7350 A current decaying with 20 seconds time constant with reasonable margin. The corrector magnets are powered individually. They have individual current leads at each cryostat. Normal conducting cables provide the current from power supplies to the magnets.

D. Development Status

In order to study the mechanical performance of the combined function magnet, a short mechanical "pancake" model, 20 cm in length, has been made. The picture of the short mechanical model is shown in Fig. 3. The model uses coil segments cut from the straight section of a practice coil that were made previously. The coil segments are encased in the plastic collar and clamped by the iron yoke. The coil segments and the yoke stack have the same length as the plastic collar. The model, therefore, simulates the 2-dimensional structure of the magnet. The model has been assembled and disassembled several times, changing assembly parameters such as coil shim thickness to check the mechanical stability of the structure. The details of the study are reported in [13].

A full-size prototype magnet of the combined function magnet is now under construction. The coils of the prototype magnet are shown in the Fig. 3. The prototype is scheduled to be completed in December 2004. The details of the prototype magnet construction are reported in [13].

Construction of a second magnet to confirm the production readiness of the design will follow the prototype magnet construction. The magnet will be made with industrial participation using the KEK tooling. The second magnet is scheduled to be completed in March 2005.

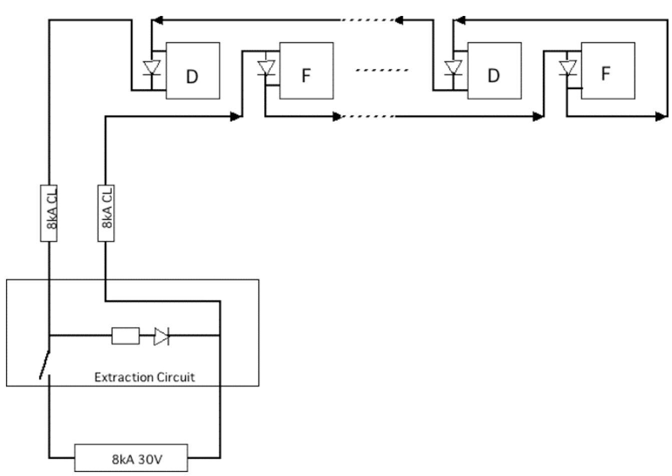

Fig. 2. Powering scheme of the combined function magnets

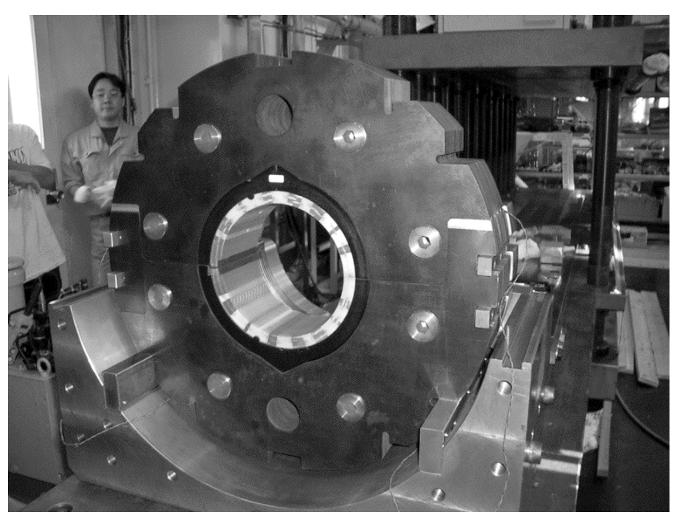
Fig. 3. Picture of the short mechanical model

Fig. 4. View from the lead end of the proto-type magnet coils. The top coil (right) and the bottom coil (left) are mirror symmetric.

III. Cryogenics

A. System Overview

The schematic flow diagram of the cryogenic system is shown in Fig. 5. The system consists of the refrigerator system, the transfer line, the cryostats, the inter-connect components, and the end boxes [14].

The refrigerator is placed in the building at ground level. The transfer line connects the refrigerator with the rest of the system components, which will be in the underground tunnel. The transfer line contains the superconducting bus that supplies a current of up to 7350 A to the magnets. The refrigerator provides supercritical helium at 0.35 MPa in pressure and 4.5 K in temperature, with a cooling power of 1.5 kW. The supercritical helium is transferred to the most upstream magnet by the transfer line, and then flows through the magnet helium vessels, which are connected in series. The helium is then expanded to produce 0.15 MPa, 4.5 K two phase helium that flows through the return pipe located in the yoke hole. The heat exchange between the supercritical helium and the two phase helium limits the temperature of the supercritical helium to a maximum of 5 K. The refrigerator also supplies 80 K helium gas to cool the 80 K shield line with a cooling power of 1.5 kW. Each cryostat is equipped with a quench relief valve. This allows helium to be released to the buffer tanks when magnets quench.

B. Cryostats

The cryostat design (see Fig. 6) is based on that of the LHC arc dipole magnets so that many of the parts are common, reducing the cost. The cryostat encases the two magnets in series, each of which is mechanically supported by two support posts. The two magnets are connected by bellows such that they are mechanically decoupled. In order to accommodate beam line radius of 105 m, they are installed so that the angle between their axes is about 2.8 degrees. The cold diode stack, which contains two diodes to protect two magnets, is installed under the cold mass at the down-stream side of the cryostat.

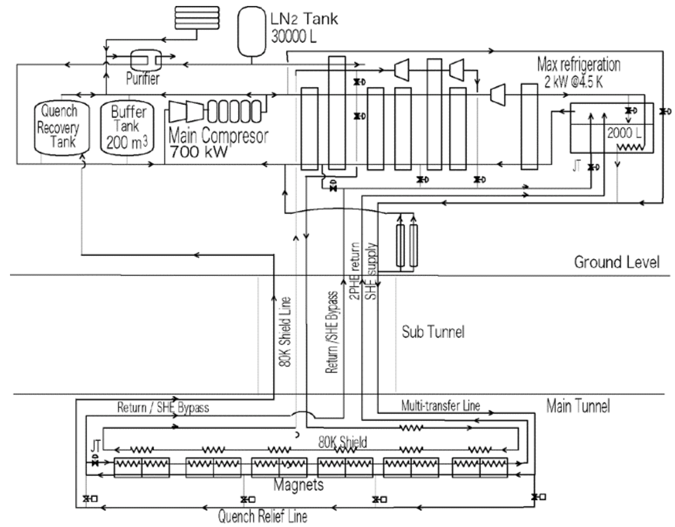

Fig. 5. Flow diagram of the cryogenics system

The heat loads for one cryostat are about 22 W to the 4.5 K main helium flow and 46 W to the 80 K shield. The total loads including that of interconnects, end boxes, transfer lines, and distribution box are about 600 W to the 4.5 K system and 1,100 W to the 80 K system.

IV. Safety Issues

A. Full Power Beam Loss

The beam line is operated in a fast extraction mode where the 50 GeV 2.7 MJ proton beam is injected every 3.6 seconds, resulting in an average beam power of 750 kW. Any failure in

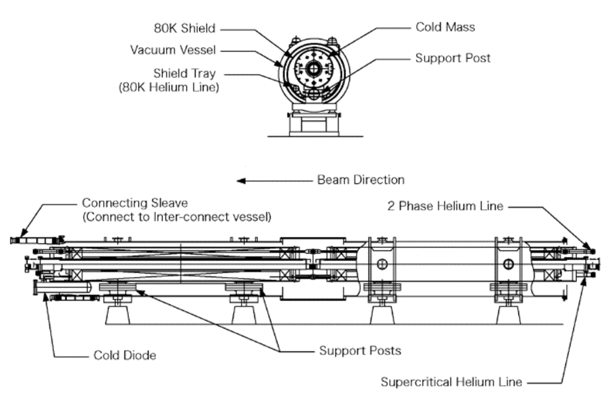

Fig. 6. Drawings of the cryostat

the beam line components can result in a direct hit of the full beam into the beam line components. The deposit of a 2.7 MJ proton beam can cause serious problems to the components. It is thus important to evaluate the issues associated with the full power beam loss.

A simulation using MARS [15] has been performed to evaluate the energy deposit from the beam. A cylindrical coaxial model that consists of the beam tube, the beam shield, and the coil was developed. The beam tube, which also serves as the helium vessel, is a stainless steel pipe with 168 mm outer diameter and 8 mm wall thickness. Inside the beam tube a beam shield is installed to reduce the energy deposit to the beam tube. The beam shield is assumed to be a copper tube with an outer diameter of 148 mm. The dependence on wall thickness has been studied. The coil is assumed to be a copper cylinder of 204 mm outer diameter and 15.3 mm thick. The beam, size of which is 10 mm times 20 mm, hits the beam shield with various incident angles. Fig. 7 summarizes the maximum dose to the beam tube as computed from the simulation model.

The maximum temperature is evaluated from the integral of the heat capacity of the stainless steel. The temperature increases from 4.5 K to 300 K with 100 kGy/pulse energy deposit. The thermal stress σ_{th} is evaluated using the formula

$$\sigma_{th} = \frac{2-\nu}{3(1-\nu)} E \int_{T_{int}}^{T_{fin}} \alpha dT$$

where ν is the Poisson ratio, E is the Young's modulus, α is the thermal expansion coefficient, T_{int} is the initial temperature, and the T_{fin} is the final temperature. The initial temperature of 4.5 K and the final temperature of 300 K give the thermal stress of 0.52 GPa. The value is comparable to the tensile strength of the stainless steel at 300 K. The maximum energy deposit allowed is thus about 100 kGy/pulse. The result indicates that even with the 10 mm thick beam shield the maximum incident angle allowed is about 0.5 degree. A direct hit of the beam having a larger incident angle must be avoided.

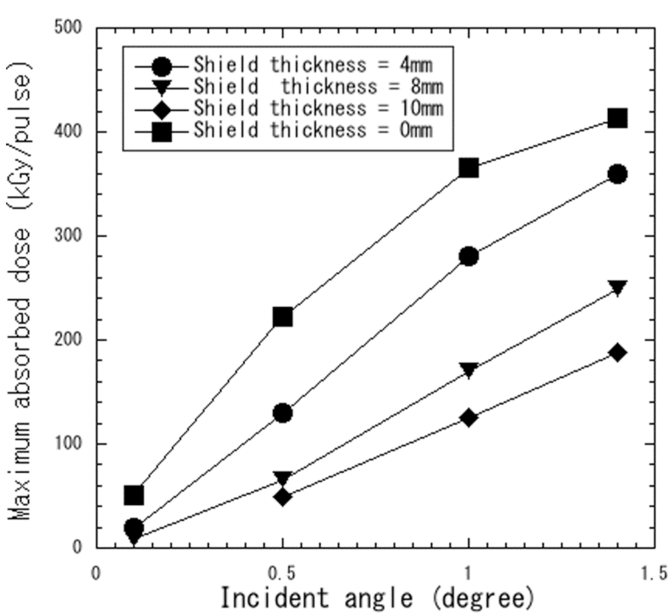

Fig. 7. Maximum dose to the beam tube by single beam incident.

A direct hit of full power beam can be critical for the magnet coil too. With an incident angle of 0.5 degrees, the coil is heated to about 220 K. The induced quench results in ohmic heating that increases the coil temperature further, to about 380 K. Incident angles higher than 0.5 degree are not tolerable from this point of view.

The effect of a beam loss of the order of 100 J/pulse, such as beam induced quenches, which can be induced by a beam halo and exists in a normal operation, are discussed in [16].

B. Quench Interlock for Beam Injection

There are several cases in which the full power beam loss can be induced. One possible case is beam injection after a magnet quench. Since the quench protection system uses cold diodes, the magnet current is automatically reduced. If the beam is injected after the current is already reduced the beam will not be guided properly and can hit the beam tube. The case can be avoided by implementing a quench detection system to prohibit beam injection after a quench. The quench detection system must detect the quench before the current is reduced. Fig. 8 shows the computed current flowing in the magnet after the quench. The computation is made with the assumption that the quench starts from the turn subjected the highest magnetic field. The result shows that the current is reduced because of the bypass to the cold diode about 90 ms after quench starts. The quench detection system must detect the quench before current is reduced with sufficient margin. A quench detection time of about 50 ms is, therefore, required for the quench detection system.

Interlocks must also be provided to protect the magnet system against other events such as power supply failure. The interlocks for the preparation section of the beam line are also very important. They should be very reliable and prevent

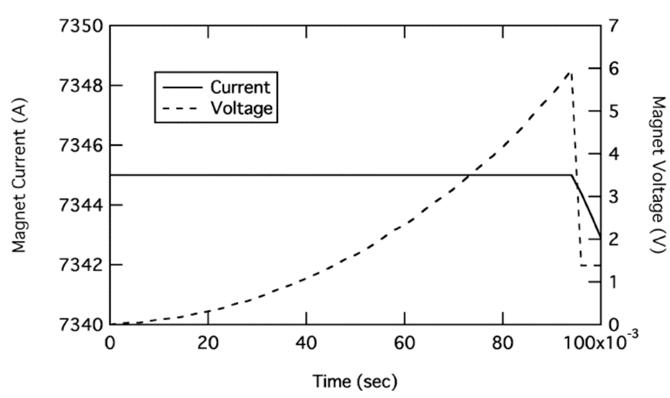

Fig. 8. Current bypass during the quench process, which starts at t=0. The quench is assumed to be started from the turn subjected the maximum magnetic field. The time to start the bypass is thus expected to be fastest.

injection when the beam line is not ready.

The last scenario which can result in a full power beam loss and relatively difficult to avoid is the failure of the kicker in the 50 GeV extraction system. Whether the beam can hit the superconducting magnet system with this scenario is now under study.

C. *Radiation Damage on Cold Diode*

As previously reported, the magnets are protected from over-heating due to a quench by the cold diodes. The cold diodes are installed in the cryostat and are subjected to radiation. The cold diodes are the same as those used for the CERN/LHC arc quadrupole magnets, and have been intensively studied for radiation damage [17][18]. The cold diodes were irradiated at CERN up to a gamma dose of about 2 kGy and a neutron fluence of about 3×10^{13} n/cm^2. The irradiation influences the forward voltage such that the maximum temperature of the diode wafer during a quench increases. In the case of J-PARC operation, the maximum wafer temperature is estimated to be 250 K with the fluence of 3×10^{13} n/cm^2, while the maximum wafer temperature allowed is 450 K. A provisional estimation indicates that a fluence of 2×10^{14} n/cm^2 corresponds to the maximum wafer temperature of 450 K. The MARS simulation performed assuming the 1 W/m line loss give a dose of 200 Gy and a fluence of 1.2×10^{13} n/cm^2 for the J-PARC configuration with an operation time of 4000 hour, which corresponds to one year operation. The results indicate that the cold diode can withstand an operation of 10 years with a sufficient margin. The maximum allowed fluence of 2×10^{14} n/cm^2, however, is derived from the extrapolation of the forward bias voltage of the diodes versus fluence. It may be desirable to confirm it experimentally. The maintenance scenario of the cold diodes is also being studied now.

V. Construction Schedule

The production schedule of the combined function magnets is as follows: 4 magnets in JFY 2005, 12 in 2006, 14 in 2007, and 2 in 2008. Installation of the magnets will be made in two phases. In the first phase, 16 magnets in 8 cryostats will be installed in the summer of 2007. In the second phase, 12 magnets in 6 cryostats will be installed in the summer of 2008. The rest of the magnets, 4 magnets in 2 cryostats, will be stored as spare magnets. The corrector magnets will be manufactured by BNL in JFY 2006 and JFY 2007. The construction of the refrigerator will start in JFY 2005 and it will be installed in JFY 2007. The rest of the cryogenic components will be constructed in JFY 2006 and installed in JFY 2007. The system will be completed with 8 cryostats for test operation, which will take in place in the winter of JFY 2007. The final commissioning of the system will start in the fall of 2008. It is planned that the beam line will be ready to accept the proton beam in January 2009.

VI. Conclusion

The superconducting magnet system for the J-PARC neutrino beam line is now under construction. The system uses superconducting combined function magnets. These magnets produce dipole and quadrupole fields by single layer left-right asymmetric coils. This is the first time a magnet of this kind will be used in a real beam line.

The beam line has to accommodate the 750 kW beam. There are various safety issues associate with the intense beam. The issues are now being intensively studied.

Acknowledgment

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